A STUDY OF HIGH-PRECISION GEOCENTRIC AND INTERPLANETARY ORBITS

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Report to
Col. John W. Querry
Chief, Applied Math Division, SRMA
Air Force Office of Scientific Research
Washington 25, D. C.

From Dr. Samuel Herrick, Principal Investigator

An informal report and inventory of research done under our contract number AF 49(638)-498, combined with a statement of our plans and purposes for our new grant number AF-AFOSR-241-63, is presented herewith:

Subject: A study of high-precision geocentric and interplanetary orbits.
Contractor: The Regents of the University of California.
Principal Investigator: Samuel Herrick.
Contract Number: AF 49(638)-498.
Technical Status Report Number: 1963-1.
Period: February 2, 1959 to April 30, 1963.

The purpose of the contract was research into the theory and application of astrodynamics in the fields of high-precision geocentric and interplanetary orbits. Developing along these parallel lines, the undertaking has continually widened and deepened in scope during the $4\frac{1}{2}$ years since its inception, to include such practical matters as the improvement of the numerical values of the astrodynamic constants, the computational advantages of various perturbation techniques, and use of universal variables, as well as theoretical development along the lines of optimization, rendezvous in space, and the adjoint method in differential orbit improvement. These will be considered in greater detail later in the report.

At the same time, the educational aspect of the contract has been continually kept in mind, resulting in published books and articles, public lectures, and extensive editorial work. In all, fifteen Astrodynamical Reports were published under the contract, by the University of California, Los Angeles, ranging over a variety of topics under the general heading of high-precision orbits. For convenience, these will be discussed under the following sub-headings:

A. Astrodynamic constants and the scale of the Solar System.
B. Orbit determination.
C. Orbit improvement, rendezvous, and the differential correction.
D. Perturbation methods and techniques.
E. Ephemerides, universal variables, and optimization.
F. Education and editorial contributions.
G. Computations.

A. Astrodynamic constants and the scale of the Solar System.

Astrodynamical Report (of the University of California, Los Angeles) No. 5, "The Astronomical Unit and the Solar Parallax," by Samuel Herrick, George B. Westrom, and Maud W. Makemson, was published in 1959. The report is concerned with the relationship between two systems of units: (a) a laboratory system consisting of the centimeter-gram-second or the foot-pound-second; and (b) the astronomical system in which the distance unit is the astronomical unit, the mass unit is the Sun's mass; and the time unit is the ephemeris day (effective from 1960), which is independent of the Earth's rotation. The effect of a small error in the solar parallax, defined as the ratio of the Earth's equatorial radius to the mean distance from Earth to Sun on minimum-energy interplanetary trajectories, is explored.

"Analysis and Standardization of Astrodynamic Constants" by Makemson, Baker, and Westrom was completed in 1960 and appeared early in 1961 as Astrodynamical Report No. 12 of the University of California, Los Angeles. The paper reviews and collates various determinations of heliocentric, geocentric, lunicentric, and planetocentric constants, and includes a table representing the atmospheric structures of Earth, Venus, and Mars, according to various models. For the purpose of standardizing computations, a consistent set of numerical values is proposed.

In 1962, the report was revised and brought up-to-date by Dr. Makemson at the request of Space Technology Laboratories for inclusion in their Flight Performance Handbook for Orbital Operations. A final version was published in 1963 by Plenum Press in Advances in the Astronautical Sciences, Vol. 8, pages 273-293, for the American Astronautical Society.

Dr. Herrick's "Scale and Mass in the Solar System," was included in Space Age Astronomy, pp. 335-346, published in 1962 by Academic Press.

As convener of the COSPAR (Committee on Space Research) Ad hoc Committee on Constants and Ephemerides, which contributed to the program for the International Astronomical Union Symposium No. 21 on "The System of Astronomical Constants," Dr. Herrick presented two papers. The first report, defining "The Needs and Uses for Constants and Ephemeral Data," outlined the requirements for space vehicles in view of modern methods and techniques of observation, with attention to the need for distinguishing astrodynamical from astronomical needs and uses. He pointed out that, in the construction of astronomical tables and ephemerides, we are primarily interested, not in the accuracy of the numerical data, but in its consistency, even though an empirical correction may be required. Accuracy, on the other hand, is of primary importance to precision space navigation as seen in the problem of landing a vehicle on a specific point on the Moon, without the requirement of complete consistency among the adopted constants.

In "The Fixing of the Gaussian Gravitational Constant and the Corresponding Geocentric Gravitational Constant," also presented to the IAU Symposium in Paris, Dr. Herrick stressed the urgent need for a reinvestigation of the whole problem of units, including such topics as:

a) the fixing of the Gaussian constant, k_s;
b) the defining of the astronomical unit in terms of k_s;
c) the proposal for the adoption of a fixed value of the terrestrial constant of gravitation, k_e;

d) the adoption of a geo-unit consistent with k_e in the same manner as the astronomical unit is consistent with k_s;

e) the possibility of the adoption of the light-second (the distance traversed by light in one second) as fundamental unit to replace the astronomical unit of distance.

Dr. Herrick discussed these questions in detail and developed equations to prove that the current use of a fixed k_s and astronomical unit is justified both by the simplification introduced into heliocentric orbit calculations and by the complications that would ensue if the astronomical unit were replaced by the light-second or the kilometer, even if radar observations of range or range-rate eventually become considerably more accurate than the optical observations of astronomy.

He pointed out that a comparable simplification would be introduced into the calculation of geocentric orbits by adoption of a geo-unit, corresponding to a fixed k_e and defined as the mean distance of a hypothetical earth-satellite of zero mass orbiting in a period of $P_o = 2\pi/k_e$. The simplification consists of the removal of first order uncertainties in the calculation of heliocentric ephemerides, in the case of k_s, and of geocentric ephemerides, in the case of k_e.

His further recommendations were discussed at the IAU Symposium in Paris, 1963 May 27-31, in COSPAR's Ad hoc Committee meeting at Paris, June 1, and finally at COSPAR's "Fourth International Space Science Symposium," held at Warsaw, June 3-12. In particular, these meetings recognized the geocentric gravitational constant as a fundamental constant and brought out new determinations of the various observational data from which it may be derived.

In Astrodynamics Research Report No. 17 of the Lockheed-California Company* (July, 1963) Dr. Herrick discussed the revision and simplification of some of the basic formulas of astrodynamical constants (e.g., determining the Moon's mass, and the solar parallax).

A detailed discussion and summary of the principal contributions to the determination of lunar astrodynamical constants since 1900 was compiled by Dr. Makemson, together with recommended numerical values for current use.

B. Orbit Determination.

In "Precision Orbits and Observation Reduction," published in June, 1959 as Astrodynamical Report No. 1 of the University of California, Los Angeles, Dr. Herrick discussed the following fundamental subjects: a) coordinate systems and the observational basis of precision orbits; b) a comparison of the four basic methods of deriving an unperturbed two-body reference orbit and the improvement by differential correction; c) the provinces of the observer and the analyst in reducing the observations to the center of the earth and making other adjustments; d) generally useful reference systems; and e) a comparison of fundamental orbit procedures.

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*Published by Lockheed-California Company. These studies were supported in part by Air Force Cambridge Research Laboratories, Office of Aerospace Research, Contract No. AF 19(628)-1619.

In July, 1960, "Orbits from Position and Velocity" by Dr. Herrick was published as Astrodynamical Report No. 8. After reviewing formulas basic to the various types of two-body orbit, i.e., the ellipse, parabola, hyperbola, the nearly circular and nearly parabolic ellipses, and rectilinear orbits, the author applied these procedures to problems of practical interest such as take-off and landing velocities, time of flight, distance and duration of a rocket flight from initial velocity and angle of elevation, and the determination of the apogee.

Dr. Baker's investigations of the determination of orbits from various combinations of range data, "Theory and Application of Range Radar to Air Force Systems," June, 1961, were tested under his supervision by Lynn Averill in a numerical application and testing of a range-only orbit determination method, which she programmed for the IBM 7090 computer. The method is based on six values of range data and the times from single station and has yielded good preliminary orbits from a variety of range-data from circular to nearly rectilinear orbits. The double-precision matrix inversion and iterative correctional procedure has yielded position and velocity within the bounds set by radar observations for three-dimensional orbits. A joint report of the work will be published by Baker and Averill.

C. Orbit Improvement, Rendezvous, and the Differential Correction. "Differential Expressions for low-eccentricity Geocentric Orbits," by S. Herrick, L. G. Walters, and C. G. Hilton was published as Astrodynamical Report No. 2 in June, 1959. Theoretically, any orbital elements may be improved by a differential correction, but special cases impose special conditions. For nearly circular orbits, for example, the parameters to be corrected must be such that the differentiation does not introduce an indeterminacy (e.g., in a division by the very small eccentricity). A 6 x 6 matrix relating the differential quantities to the corrections to the parameters for orbits of low eccentricity is presented in Table II. Section 5 derives the differential corrections to the six parameters in terms of the residuals in range and range-rate only. These formulas are especially applicable to single-site electronic observing stations.

Astrodynamical Report No. 15, "Two-body Precision Aspects of Rendezvous," by Samuel Herrick, was published in February, 1963. Based upon the well known expressions for the f and g series, by which the position and velocity of a vehicle can be found at any time from the initial position and velocity at the epoch, and upon the "closed expressions" for elliptic orbits, differentiations lead to expressions that can be used both for the mathematical correction of an approximate orbit into one that better satisfies the observations, and for the thrust correction of a non-intercepting orbit into one that will intercept. The author extends these procedures and formulations to his universal variables so that they can be used even if the orbit passes through either zero (the circular orbit) or unity (the parabolic orbit, or the rectilinear ellipse or hyperbola). The principal aim of the paper is its application to the problem of rendezvous or interception: Given, the position and velocity of the intercepting vehicle at the time t_0, when thrust is to be applied, and given, the position and velocity of the target vehicle at the time, t, when rendezvous is to take place, to determine accurately the velocity which must be achieved in order to correct the interceptor's velocity by thrust in order to reach rendezvous at time, t. The formulas are in a form which admits

the addition of perturbation terms.

Gun Ohlsson programmed for the 7090 computer Dr. Herrick's standard differential correction procedure for elliptical orbits with large or moderate eccentricities. The program involves a least squares inversion and can handle up to 60 observations in right ascension and declination. The program has been applied to Minor Planet Icarus, with attention to difficulties that arise in the matrix inversion when the observations are not sufficiently separated in time. It is planned to apply the program to Minor Planets Betulia and Geographos.

D. Perturbation Methods and Techniques.

The all-important subject of perturbation techniques received considerable attention during the period of the contract. Astrodynamical Report No. 3 "Efficient Precision Orbit Computational Techniques," by R.M.L. Baker, Jr., George B. Westrom, C. G. Hilton, Jeannine L. Arsenault, R. H. Gersten, and Elsie Browne was published in June, 1959. In it, the authors made a critical review of the three general methods of dealing with special perturbations by numerical integration to determine what procedure is most effective in the various types of artificial satellite and space probe orbits. They found, as expected, that the choice of method depends on the nature of the individual problem. For high perturbative forces, for example in re-entry, Cowell's method is indicated superior. In the case of small or moderate perturbative forces acting all around the orbit, as in low-thrust interplanetary voyages, the variation of parameters procedure is preferable. When small or moderate perturbative forces act over a restricted segment, as in a lunar landing or certain ballistic interplanetary trajectories, Encke's method is superior. In evaluating the quantitative results, a clear distinction was made between truncation errors and those which accumulate from rounding in the numerical integration.

"Three-dimensional Drag-Perturbation Technique," by R.M.L. Baker, Jr., was published in August, 1960 as Astrodynamical Report No. 4. This work was an extension to three dimensions of the author's earlier analysis of perturbation procedures as applied to re-entry of space vehicles into the Earth's atmosphere (i.e. gravity-free drag orbits). Although presented for the geocentric case, the equations are equally appropriate to the satellites of other planets. In addition to drag due to a resisting medium, the effects of the Earth's oblateness and of other irregularities in its potential field are included in the perturbative accelerations. Methods for handling ablation, atmospheric rotation, cross-winds, lift and transitional drag are also discussed.

Astrodynamical Report No. 9 (July, 1960) presents "The Variation of Parameters," by Samuel Herrick, a method of special perturbations in which perturbative changes in the orbital elements (or some function of them) are numerically integrated to produce the disturbed motion at any instant. The effect of the author's modifications of the method, as in the integration of the vectors $\underline{a} = e\underline{P}$ and $\underline{b} = e\sqrt{p}\,\underline{Q}$ and of the mean daily motion and mean anomaly, is to shorten the calculation and to introduce checks that were not possible in the older procedures. The advantage of Dr. Herrick's method

over the Cowell method of special perturbations, in which the entire differential equation of motion is integrated, and over the Encke method, in which the differences between the rectangular coordinates of the disturbed and undisturbed motions are integrated, lies partly in the fact that it yields the elements directly, partly in the achievement of higher accuracy for fewer integration steps.

The variation-of-parameters procedure outlined by Dr. Herrick in Astrodynamical Report No. 9 was programmed by Mrs. Mary Francis for the IBM 7090 computer. As soon as magnetic tapes of the coordinates of the planets are received from Jet Propulsion Laboratory, the program can be run over a 20-year arc for Minor Planets Icarus, Betulia and Geographos.

Mrs. Francis also completed an IBM 7090 program for a Cowell integration on Jupiter's Satellites IX and XII. Lynn Averill calculated 1963 ephemerides of these satellites for the Publications of the Astronomical Society of the Pacific. She also derived ephemerides for Icarus and Geographos. Mrs. Francis' ephemeris of 1580 Betulia appeared in Minor Planet Circulars.

"A Comparison of Astronomical and Ballistic Traditions in Orbit Computation" by Samuel Herrick was published in May, 1962 as Astrodynamical Report No. 14. In it, the author explores the following topics: (1) comparison between astronomical differential correction methods for improving an orbit, etc., with the "adjoint method," which has come into space navigation from ballistics; (2) problems in observational differential corrections and in rendezvous or targeting; (3) residuals or miss-components in $\underline{r}$, the position vector at the time $\underline{t}$ referred to the dynamic center; and (4) correction of the position and velocity vectors r_o and $\dot{r}_o$ at the epoch t_o.

When the differences between $\underline{r}$ (the observed or "objective" position vector) and $\underline{r}_c$ (the calculated value) or between $\underline{\dot{r}}$ and $\underline{\dot{r}}_c$, the observed or "objective" velocity vector and its calculated counterpart are expressed in terms of the corrections to the rectangular coordinates and velocities at the epoch, as unknowns, the equations contain 36 partial differential coefficients which must be evaluated numerically before the equations can be solved. This paper compares and analyses five methods for determining these differential coefficients, i.e., (a) by analytic differentiation of the formulas used for representing an observation, neglecting perturbations; (b) by a variant calculation in which each parameter is allowed to vary individually (e.g. by Cowell's method of special perturbations); (c) by a variant method based on Encke's method of special perturbations; (d) by the "adjoint method," in which linearized variants are integrated backward to yield the partial differential coefficients directly; (e) by a linearized version of (c) resembling (d) but integrated in a forward direction.

The adaptation of these methods to machine computation and their application to such specific problems as rendezvous or homing on a target are discussed in this basic paper.

E. Ephemerides; Universal Variables; Optimization.

Traditionally, the orbit of a celestial body was either an ellipse (with the circle and parabola as limiting cases for e = 0 or 1) or hyperbola, in

rare cases of comets passing too close to Jupiter. No provision was made for variable trajectories met with today in the motions of space vehicles. An interplanetary vehicle, for example, may leave the earth on a geocentric hyperbola, change smoothly into a heliocentric ellipse, and arrive at the target on a planetocentric hyperbola.

One of the most valuable and far-reaching contributions to astronautics that has developed under the Air Force Contract is Dr. Herrick's introduction of "universal variables" and formulas and their practical application to specific cases. These make it possible to integrate the orbit over the entire range of eccentricities without its becoming indeterminate at critical points. Astrodynamical Report No. 7 (July, 1960): "Positions, Velocities and Ephemerides Referred to the Dynamic Center," by Dr. Herrick, treats of the general topic of ephemeris integration from the position and velocity vectors, $\underline{r}$ and $\dot{\underline{r}}$.

For a variable trajectory, when the vehicle is subject to perturbative forces such as thrust and drag, or when a differential correction carries the orbit over from one conic to another, Dr. Herrick develops universal formulas in universal variables, applicable to all conics and to the rectilinear ellipse, parabola and hyperbola. The final section presents formulas for the development of series in Bessel's functions and related series in powers of the eccentricity employed in general perturbation theory.

Stimulating exercises appended to each section and several numerical examples add to the interest and scope of this comprehensive investigation.

Similarly, Astrodynamical Report No. 14 (discussed under D of this report) contains "universal formulation" for circles, ellipses, parabolas, hyperbolas, and to rectilinear orbits and extends the use of universal variables to the relationships among the differentials of the various parameters to $\underline{r}$ and $\dot{\underline{r}}$, and finally to the problem of "homing on a target" or rendezvous.

An important aspect of astronautics which demands particular attention at this time is the theory of optimization, which includes the determination of the exact trajectory between two points (e.g. the earth and target moon or planet) which calls for a minimum expenditure of energy. The Contract has been fortunate in having the technical assistance of Mr. Robert S. Long, instructor in mathematics at the University of Canterbury in Christchurch, New Zealand, for one year beginning January 1, 1963. Mr. Long is a specialist in the theory of optimization of rocket trajectories.

His principal areas of research since his arrival here have been:

(a) Co-operation with Dr. Herrick in some aspects of orbit theory, including its interdependence with optimization.

(b) Studies in trajectory optimization in the following areas, with emphasis on new methods in the first and third: (1) Estimation of suitable initial values. (2) Suitable integration schemes. (3) Suitable iteration schemes.

(c) Preparation of lectures on the calculus of variations and trajectory optimization theory, which he presented to the classes in astrodynamics.

(d) Frequent discussions and exchange of ideas with E. T. Pitkin in connection with the latter's work on the use of the gradient method and universal variables in optimization.

(e) Study of orbit determination in general.

Mr. Long will be concerned with further development of the relationships between optimization theory and orbit determination during his appointment under the Air Force Contract.

Mr. Edward T. Pitkin's numerical application of optimization theory with the use of universal variables should produce valuable information for space trajectories in the near future.

F. Educational and Editorial Contributions.

During the entire term of the Contract, Dr. Herrick has worked (as time permitted) on the revision of various chapters of Astrodynamics, adding numerical examples and applications to current astronautical problems. Several of these chapters have been published individually to meet immediate needs.

Dr. Herrick also served as Jerome Clarke Hunsaker professor of Aeronautics and Astronautics during 1961-62, at the Massachusetts Institute of Technology. His other activities included: the Board of Directors of the American Rocket Society; Commissions 7 and 20 of the International Astronomical Union; and the Board of Directors and the Technical Activities Committee of the American Institute of Aeronautics and Astronautics. He was Sponsor in Astrodynamics of the American Society of Mechanical Engineers, and Minta Martin Lecturer of the Institute of Aerospace Sciences. He was awarded an Honorary Doctor of Science degree by Williams College. He served as chairman of the Astrodynamics Committee of the American Rocket Society and was elected Fellow of the American Astronautical Society. One of his most important contributions was as convener of an ad-hoc committee of COSPAR, which contributed to the program on astrodynamic and astronomical constants for the 21st Symposium of the International Astronomical Union, and reported on the need for COSPAR activity in this field to the Warsaw meeting of the council of that organization, June, 1963.

"Introduction to Astrodynamics," by R.M.L. Baker, Jr., and Maud W. Makemson, first appeared in the spring of 1960 as Astrodynamical Report No. 6. It was published by Academic Press in October, 1960, and is now in its third printing. Dr. Baker and Dr. Makemson are in the process of revising the book completely and bringing it up-to-date. Academic Press will publish the new edition in the winter of 1963-64.

Dr. Herrick was made coordinating editor of the section on Astrodynamics in the HANDBOOK OF ASTRONAUTICAL ENGINEERING, McGraw-Hill, 1961. Sections 4.1 and 4.2 on coordinate systems, celestial mechanics, orbital elements and position in orbit, were contributed by Dr. Makemson; section 4.3 on perturbations due to drag, thrust, and the earth's asphericity, by Dr. Baker; and

sections 4.4 and 4.5 on trajectory constants and their improvement by the use of artificial satellites, by G. B. Westrom.

"Analysis and Standardization of Astrodynamic Constants" by Makemson, Baker, and Westrom was published as Astrodynamical Report No. 12, in February, 1961. There were many requests for copies of this paper, a version of which also appeared in the Journal of Astronautical Sciences in the Spring of 1961. When Space Technology Laboratories asked permission to include this report in their "Flight Performance Handbook for Orbital Operations," in 1962, Dr. Makemson revised the paper and brought it up-to-date. It was also published by the American Astronautical Society in "Advances in the Astronautical Sciences," Vol. 8, Plenum Press, 1963.

A long and arduous task was achieved by Dr. Baker and Makemson during 1962 in the editing of the Proceedings of the International Astronautical Federation Congress, which met in Washington during the week of October 1, 1961, with Dr. Herrick representing the American Astronautical Society as chairman. The 900-page, two-volume edition of the Proceedings was published jointly by Springer-verlag (Vienna) and Academic Press, under the editorship of Drs. Baker and Makemson.

"Recent Advances in Astrodynamics, 1961" by R.M.L. Baker, Jr., and Mary P. Francis, appeared in January, 1962 as Astrodynamical Report No. 13. The report indicated that the amount of literature published in 1961 in the field of coordinates and ephemerides, constants, planetary atmospheres, orbit determinations, perturbation techniques, effects of solar radiation and magnetic forces, and so on, had doubled over the 1960 output.

The advisability of standardizing scientific symbols, notation, and terminology on the basis of established conventions and usage, nowhere more evident than in Astrodynamics which represents a fusion of several fields, led to the publication of "Astrodynamical Notation and Usage," by S. Herrick, M. W. Makemson, and M. F. Francis as Astrodynamical Report No. 10, August, 1960. The paper is founded on the philosophy that, whereas usage should be the principal criterion, alternative notations should also be allowed, as the result either of usage or of the logical development, wherever conflicts have occurred.

Other publications under the Contract include:

Abstracts of Astrodynamical Reports Nos. 1-13 were compiled by Dr. Makemson, and submitted to Capt. Gilbert for publication in the AFOSR weekly activity reports. Short articles: "Icarus and the Space Age," and "Ephemeris Time and Universal Time," by Dr. Makemson were published as Astronomical Society of the Pacific Leaflets in 1962 and 1963. A paper entitled, "Old and New Beliefs about the Earth's Figure" was presented by Dr. Makemson at the International History of Science Congress at Cornell University in August, 1962. The paper dealt with new facts learned about the Earth from close orbiting satellites.

G. Computation.

In addition to the calculations already referred to in the Report, the

following work was performed by T. O. Montgomery prior to June, 1961, under the supervision of G. Hilton, for the purpose of testing space navigation formulas on the orbits of natural astronomical objects:

1. Representation of observations of Minor Planet (1620) Geographos, including perturbations by the earth, Jupiter, and Saturn by Encke's method.

2. Representation of the observations of Jupiter's ninth and twelfth satellites, including perturbations by the sun and Saturn, by Cowell's method.

3. Two differential corrections by Herrick's method for nearly circular orbits including one least squares solution for a new Trojan Minor Planet, 1957 MK, discovered by Nicholson at Palomar Observatory. This differential correction method was also applied to the design orbit of the Mercury capsule, at Aeronutronic, a Division of the Ford Motor Company.

Other computations executed under the Contract include the following:

Elements of (1566) Icarus, (1580) Betulia, and (1620) Geographos, by S. Herrick, C. G. Hilton, and W. P. Hirst. Minor Planet Ephemerides 1960, Leningrad, 1959.

Ephemerides of Jupiter's satellites IX and XII for 1960 by S. Herrick and T. O. Montgomery, Harvard Announcement Cards 1478, 1480; Publ. Astron. Soc. Pacific 72:131, 1960.

Ephemerides of (1580) Betulia and (1566) Icarus for 1960, by S. Herrick and T. O. Montgomery, Harvard Announcement Cards 2004 and 2005, 1960.

Ephemerides for Jupiter's ninth and twelfth satellites for 1963, by S. Herrick, Lynn Averill, and Mary P. Francis, Pub. Astron. Soc. Pacific, 1963.

I. Summary of Publications

A. Astrodynamical Reports

Herrick, Samuel. Precision orbits and observation reduction. U.C.L.A. Astrodynamical Report No. 1, University of California, Los Angeles, June 11, 1959; AFOSR TN-59-769; Aeronutronic Publ. U-386.

Herrick, Samuel, L. G. Walters and C. G. Hilton. Differential expressions for low eccentricity geocentric orbits. U.C.L.A. Astrodynamical Report No. 2, University of California, Los Angeles, June 11, 1959; AFOSR TN-59-768; Aeronutronic Publ. U-456.

Baker, Robert M. L., Jr., George B. Westrom, C. G. Hilton, Jeannine C. Arsenault, Robert Gersten, and Elsie Browne. Efficient precision orbit computation techniques. Astrodynamical Report No. 3, University of California, Los Angeles, June 11, 1959.

Baker, Robert M. L. Jr. Three-dimensional drag perturbation technique. U.C.L.A. Astrodynamical Report No. 4, University of California, Los Angeles, July 1, 1959. AFOSR TN 59-767; reprinted from the ARS Journal, August 1960.

Herrick, Samuel, G. B. Westrom, and Maud W. Makemson. "The astronomical unit" and the solar parallax. U.C.L.A. Astrodynamical Report No. 5, September 30, 1959; AFOSR TN 59-1044; Appendix G Aeronutronic Publ. U-583, September 28, 1959.

Baker, R.M.L., Jr., and M. W. Makemson. Introduction to Astrodynamics, New York; Academic Press, 1960. (was Astrodynamical Report No. 6)

Herrick, Samuel. Positions, velocities, ephemerides referred to the dynamical center. U.C.L.A. Astrodynamical Report No. 7, July, 1960. AFOSR TN 60-773.

Herrick, Samuel. Orbits from position and velocity. U.C.L.A. Astrodynamical Report No. 8, July, 1960. AFOSR TN 60-816.

Herrick, Samuel. The variation of parameters, Chapter 17. (Newport Beach, Aeronutronic, September, 1959.) U.C.L.A. Astrodynamical Report No. 9, July, 1960. 62pp. AFOSR TN 60-812.

Herrick, Samuel, Maud W. Makemson, and Mary P. Francis. Astrodynamical notation and usage. U.C.L.A. Astrodynamical Report No. 10, August, 1960. AFOSR TN 60-856.

Baker, Robert M. L., Jr. Recent advances in astrodynamics, 1960. Astrodynamical Report No. 11, October, 1960. AFOSR TN 60-1231

Makemson, Maud W., R. M. L. Baker, Jr., and G. B. Westrom. Analysis and Standardization of Astrodynamic Constants. U.C.L.A. Astrodynamical Report No. 12, December, 1960. AFOSR TN 61-128. (Revised by Dr. Makemson, 1962, Advances in the Astronautical sciences, 8, 1963. pp 274-293, Prenum Press. Flight Performance Handbook for Orbital Operations (Space Technology Lab. John Wiley and Sons, 1963.

Baker, Robert M. L. Jr., and Mary P. Francis. Recent Advances in Astrodynamics 1961. U.C.L.A. Astrodynamical Report No. 13, January, 1962. AFOSR 2551.

Herrick, Samuel. A comparison of astronomical and ballistic traditions in orbit computation. U.C.L.A. Astrodynamical Report No. 14, May 1962; Dynamics of Satellites, pp 51-64.

Herrick, Samuel. Two body precision aspects of rendezvous. Lockheed Spacecraft Report, August 1961 (preliminary version); Astrodynamics Research Report No. 11, Lockheed-California Co. (LR16197), August 1962; U.C.L.A. Astrodynamical Report No. 15, Feburary 1963.

B. Periodical Articles

Baker, R.M.L. Jr. "The Return from Interplanetary Voyages," J. British Interplanetary Soc., May-June, 1959, 93-97, Vol. 17, #3

Baker, R. M. L. Jr. "The Application of Astronomical Perturbation Techniques to the Return from Space Voyages," ARS Journal, March 1959, 29, No. 3, 207-211.

Baker, R. M. L. Jr. "Sputtering as it is Related to Hyperbolic Meteorites," J. Applied Physics, 30, No. 4, April 1959, 550-555.

Baker, R.M.L. Jr. "Transitional Aerodynamic Drag of Meteorites," Astrophysical Journal, 129, No. 3, May 1959, 826-841.

Baker, R.M.L. Jr. "The Sky is the Limit for Opportunities in Astrodynamics," IRE Student Quarterly, May 1959.

Baker, R.M.L. Jr. "Review of Celestial Mechanics by E. Finley-Freundlich," Publ. of Astronomical Soc. of the Pacific, 71, 352-3, 1959.

Baker, R.M.L. Jr. and Samuel Herrick. "Astrodynamics," Astronautics, 4, No. 11, pp. 30, 180-1, 1959.

Baker, R.M.L. Jr. "Effect of Accommodation on the Transitional Aerodynamic Drag of Meteorites," Astrophysical Journal, 130, No. 3, 1024-1026, November 1959.

Baker, R.M.L. Jr. "Training in Astronautics," Space, December 1959.

Baker, R.M.L. Jr. "Liberations on a Slightly Eccentric Orbit," ARS Journal, 30, No. 1, 124-126, January 1960.

Baker, R.M.L. Jr. "Librations of a Prolate Ellipsoidal Shell, ARS Journal, 30 No. 1, 126-128, January 1960.

C. Published Materials from Meetings

Herrick, Samuel. "Earth satellites and related orbit and perturbation theory." Space Technology (ed. J. S. Seifert; New York McGraw-Hill (1959), pp. 5-01 --5-30.

Herrick, Sameul. "Ephemerides, representations, observational reference systems and data" Astrodynamics, Chapter 10, (Glendale, Aeronutronic Systems, Inc., November, 1959.)

Herrick, Samuel. "Differential representations, corrections and error analyses," Astrodynamics, Chapter 14. (Newport Beach, Aeronutronic, June 1959.)

Baker, R.M.L., Jr., "Preliminary Orbit Determination." presented at the International Symposium on the Dynamics of Satellites in Paris, France, May, 1962.

Makemson, M. W., "Old and new ideas about the earth's figure." presented at the International history of Science Congress, at Cornell University, August 1962.

Herrick, Samuel. Astrodynamics: State of the art, 1959. (With Robert M. L. Baker, Jr.) Astronautics, 4, p. 30, November 1959; U.C.L.A. Astron. Pap., 2, No. 6, 1959.

Makemson, M. W., and R.M.L. Baker, Jr. (editors), Proceedings of the XII International Astronautical Federation Congress, Washington D.C., 1961, 2 Volumes 900 printed pages.

Makemson, M.W., R.M.L. Baker, Jr., G. W. Westrom. "Analysis and standardization of astrodynamic constants." (revised, 1962, Advances in the astronautical sciences, 8, 1963. pp. 274-293, Prenum Press. Flight Performance Handbook for Orbital Operations (Space Technology Lab.), John Wiley and Sons, 1963.

D. Other Publications

Herrick, Samuel. With members of the Rand Corporation. Space Handbook, Astronautics and its applications. 85th Congress, 2nd Session. (United States Government Printing Office, Washington; 1959; 2nd ed., New York, Random House, 1959.)

Herrick, Samuel. Ephemerides, representations, observational reference systems and data. Astrodynamics, Chapter 10, (Glendale, Aeronutronic Systems, Inc., November, 1959.)

Herrick, Samuel. (With C. G. Hilton) 1959 ephemerides of Jupiter's ninth and twelfth satellites. Publ. A.S.P., 71, 172, April 1959.

Herrick, Samuel. Differential representations, corrections and error analyses, Astrodynamics, Chapter 14. (Newport Beach, Aeronutronic, June 1959.)

Herrick, Samuel. Astronomy session (Chairman). Proc. Lunar and Planetary Exploration Colloq., 2, No. 1, 34-48, September 23, 24, 1959.

Herrick, Samuel. Elements of (1566) Icarus, (1580) Betulia, and (1620) Geographos. (With C. G. Hilton and W. P. Hirst.) Ephemerides Minor Planets, 1960. (Leningrad, 1959.)

Herrick Samuel. (With T. O. Montgomery) H.A.C 1478, April 14, 1960. Authors acknowledged H.A.C. 1480. Also Pub. A.S.P. 72, 131-32, April 1960.

Herrick, Samuel. Position and velocity orbits from incomplete observations. Astrodynamics, Chapter 12. (Newport Beach, Aeronutronic, April 1960.)

Herrick, Samuel. Orbits from several incomplete position observations. Astrodynamics, Chapter 13. (Newport Beach, Aeronutronic, April 1960.)

Herrick, Samuel. Ephemeris of (1580) Betulia. (With T. O. Montgomery) M.P.C. 2004, May 9, 1960.

Herrick, Samuel. (With T. O. Montgomery) Ephemeris of (1566) Icarus. M.P.C. 2005 May 26, 1960.

Herrick, Samuel. Observation requirements for precision orbit determination. Aeronautics and Astronautics, pp. 417-434. (New York-London, Pergamon, 1960.) U.C.L.A. Astron. Pap., 3, No. 4, 23-40.

Herrick, Samuel. (With T. O. Montgomery.) Elements and 1961 ten-day ephemerides of (1566) Icarus, (1580 Betulia, and (1620) Geographos. Ephemerides Minor Planets, 1961, pp. 42, 43, 146, 154, 157. (Leningrad, 1960.)

Herrick, Samuel. (With Lynn Averill and T. O. Montgomery.) 1961 ephemerides of Jupiter's ninth and twelfth satellites. Pub. A.S.P., 73, No. 431, 168-169, April 1961.

Herrick, Samuel. The orbits of asteroids and meteors. Proc. Lunar and Planetary Exploration Colloq., 2, No. 4, 12 - 14 November 16, 1961.

Herrick, Samuel, Scale and mass in the solar system. Space Age Astronomy, pp. 335-346. (New York-London, Academic Press 1962.)

Herrick, Samuel. Encke's method using r_0, r_0 as parameters together with both elliptic and universal variables, both for normal integration and for obtaining partial differentail coefficients. Section V of Lockheed Astrodynamics Research Center Interum Technical Report, September 17, 1962.

Herrick, Samuel. 1580 Betulia. Handbook, British Astronomical Association, 1963, p. 27 November 1962.

Herrick, Samuel. (With Mary P. Francis.) Elements and 1963 ten-day ephemeris of (1580) Betulia. Ephemerides Minor Planets, 1963, pp 43, 94. (Leningrad, 1962.)

Herrick, Samuel. (With Mary P. Francis, Lynn Averill, Fun Ohlsson.) 1963 two-day and four-day ephemeris of (1580) Betulia. H.A.C. 1580, 1602, January 3, June 7, 1963; M.P.C. 2165-2166, January 7, 1963.

Herrick, Samuel. Rendezvous and mid-course guidance and control. (Outline lecture notes for University California Lunar Missions and Exploration Lecture No. 7, April 1-4, 1963.)

Makemson, Maud W. Leaflet of the Astronomical Society of the pacific No. 397, July 1962: "Icarus and the Space Age."

Makemson, Maud W. Leaflet on "Ephemeris Time and Universal Time" #407, May, 1963.

II. Summary of meetings attended and papers presented:

February 18-23, 1959; IAS and Lockheed Aricraft at Palo Alto and Berkeley, California; Dr. Herrick delivered papers on "Interplanetary Navigation" and "Astrodynamics."

June 8-11, 1959; American Rocket Society Meeting; San Diego, California; Dr. Herrick chairman of the session on Astrodynamics.

June 17-24, 1959; Institute of Navigation; New York, Dr. Herrick's paper on "Contrasting Sea, Air and Space Navigation."

August 7-8, 1959: Durand Centennial Conference, Palo Alto, California; Dr. Herrick lectured on "Observation Requirements for Precision Orbit Determination."

August 27-September 12, 1959; Fourth International Astronautical Congress, London, England, Dr. Herrick's paper, "Differential Expressions for Low Eccentricity Orbits." Also in Washington for the Conferences with Air Force General Boushey, NASA, Etc.

September 16, 1959; IAS Frontiers of Science and Engineering Colloquium, U.C.L.A.; Dr. Herrick presented paper on "Astronautical Constants."

August 16, 1960; International Astronautical Union, Stockholm, Sweden; Dr. Herrick's presentation, "Trajectories above the Denser Portions of the Earth's Atmosphere."

November 18, 1960; Joint meeting of the British Interplanetary Society and British Institute of Navigation, London, England; Dr. Herrick's presentation, "The Demands of Nearly Parabolic Lunar Trajectories on Differential Correction and Perturbation Theory."

December 2, 1960; American Society of Mechanical Engineers, Washington, D.C.; Dr. Herrick's presentation, "Astrodynamics and Engineering."

January 16-18, 1961; American Astronautical Society, Dallas, Texas; Dr. Herrick chairman of the session, and Dr. R.M.L. Baker, G. W. Westrom attended, "Analysis and Standardization

June 27-29, 1961; AFOSR-GE Symposium on Analytical Astrodynamics, Los Angeles, Calif.; attended by Dr. Herrick and Dr. Baker, "The Selection of Parameters and Independent Variables for Perturbation Integration."

August 7-9, 1961; Space Age Astronomy Symposium, Pasadena, California; Dr. Herrick presented "Scale and Mass in the Solar System."

August 13-25, 1961; International Astronomical Union, Berkeley, California; Dr. Herrick was a member of Commission 7, paper on "Celestial Mechanics."

October 2-7, 1961; XIIth International Astronautical Congress, Washington, D.C.: Dr. Herrick served as chairman, and Drs. Baker and Makemson were the editors of the proceedings of the congress. Dr. Baker also served as organizer of the astrodynamics sessions.

October 9-13, 1961; American Rocket Society's Space Flight Report to the Nation, New York City.

Februa y 22-26, 1962; Working symposium on Solar System Constants at the RAND Corporation, Santa Monica, Calif.; attended by Drs. Herrick and Baker, and Mrs. M. P. Francis.

April 26-28, 1962; COSPAR Symposium on the Use of Artificial Satellites for Geodesy, U. S. Naval Observatory, Washington D.C., attended by Drs. Herrick and Baker.

May 28-31, 1962; International Symposium on the Dynamics of Satellites in Paris, France, attended by Drs. Herrick and Baker.

August 27-31, 1962; The 4th International Symposium on Space Technology and Science 1962, Tokyo, Japan; attended by Dr. Herrick.

November 13-18, 1962; American Rocket Society, Los Angeles, California; attended by Drs. Herrick and Baker, Miss Averill, and Miss G. Ohlsson; Dr. Herrick presented a paper, Dr. Baker was on a panel discussion.

December 27-29, 1962; American Astronomical Society One Hundred-twelfth Meeting Attended.

January 15-17, 1963; Ninth Annual American Astronautical Society Meeting, Statler-Hilton Hotel, Los Angeles, Calif.; elected to Fellow membership in the AAS. (Dr. Herrick)

January 18, 1963; Space Sciences Colloquiem College of Engineering, University of Washington, Dr. Herrick a keynote speaker in the field of Astrodynamics.

April 22-24, 1963; AIAA 2nd Manned Space Flight Meeting; Marriott Motor Hotel, Dallas, Texas, Dr. Herrick attended.

III. Additional Information.

Personnel who have engaged in research work during the period of contract, from February 2, 1959 to April 30, 1963:

Dr. Samuel Herrick	Principal investigator (uncompensated) From February 2, 1959 to April 30, 1963.
Dr. Robert M.L. Baker, Jr.	Associate investigator (uncompensated) From February 2, 1959 to April, 1963.
Mr. Charles Goeffrey Hilton	Associate investigator (uncompensated) From February 2, 1959 to October, 1959.
Dr. Maud W. Makemson	Associate investigator From April 27, 1959 to December 31, 1962. Leave of absence from January 1 to April 30, 1963.
Mrs. Mary Francis	Graduate research astronomer (uncompensated) From July 6, 1959 to July 31, 1962.
Mr. George Westrom	Research Assistant From July to September, 1959.
Mr. Thomas O. Montgomery	Research assistant March 23, 1959 to June, 1961.
Mr. Theodore Fine	From May 8, 1962 to February, 1963. Graduate research astronomer.
Mr. Robert S. Long	Research specialist. From January, 1963 to April 30, 1963.
Miss Lynn Averill	Research assistant (uncompensated since July, 1962) From March 10, 1960 to April 30, 1963.
Miss Gun I. Ohlsson	Research assistant From July, 1961 to April 30, 1963.
Miss Jean L. Swain	Secretary to chief investigator From February 16, 1959 to June, 1960.
Miss Rachel Quiros	Steno secretary to chief investigator From April, 1961 to November, 1962.
Miss Joan Boyle	Steno secretary, part time 13.75% From August, 1961 to April 30, 1963.
Mrs. Shirley Cockerill	Secretary to chief investigator From November, 1962 to February 8, 1963.
Miss Keiko Watanabe	Steno secretary to chief investigator From February 11 to April 30, 1963.

IV. Summary of Appointments held and honors received.

Samuel Herrick: Jerome Clarke Hunsaker, Professor, 1961-1962, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology; Member of Board of Directors, American Rocket Society; Member of Commission 7, International Astromical Union; Sponsor in Astrodynamics, American Society of Mechanical Engineers, Minta Martin Lecturer, Institute of Aerospace Sciences; Honorary Doctor of Science, Williams College; Member of Technical Activities Committee, AIAA: Chairman of Astrodynamics Committee, American Rocket Society.

Robert M. L. Baker, Jr.: Co-Editor, Proceeding of the XIIth International Astronautical Congress; Member of Astrodynamics Committee, American Rocket Society; Chairman of Astrodynamics Committee, American Institute of Aeronautics and Astronautics; Editor, Journal of the Astronautical Sciences; Sponsor of Astrodynamics, American Society of Mechanical Engineers; editor, Journal of Astronautics; Vice-chairman of Astrodynamics, American Rocket Society.

Maud W. Makemson: Co Editor, Proceedings of the XIIth International Astronautical Congress.

Lynn Averill: Master of Arts, Astronomy, University of California, Los Angeles.